

NASA Technical Memorandum 102434
AIAA-90-0783

Applications of High Thermal Conductivity Composites to Electronics and Spacecraft Thermal Design

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Prepared for the
13th International Communication Satellite Systems Conference
sponsored by the American Institute of Aeronautics and Astronautics
Los Angeles, California, March 11-15, 1990



(NASA-TM-102434) APPLICATIONS OF HIGH
THERMAL CONDUCTIVITY COMPOSITES TO
ELECTRONICS AND SPACECRAFT THERMAL DESIGN
(NASA) 8 p

CSCS 228

N92-24349

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APPLICATIONS OF HIGH THERMAL CONDUCTIVITY COMPOSITES TO ELECTRONICS AND SPACECRAFT THERMAL DESIGN

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Abstract

Recently, high thermal conductivity graphite fiber-reinforced metal matrix composites (MMC's) have become available that can save weight over present methods of heat conduction. These materials have two to three times higher thermal conductivity in the fiber direction than the pure metals when compared on a thermal conductivity-to-weight basis. Use of these materials for heat conduction purposes can result in weight savings of from 50 to 70% over structural aluminum. Another significant advantage is that these materials can be used without the plumbing and testing complexities that accompany the use of liquid heat pipes. A spinoff of this research was the development of other MMC's as electronic device heat sinks. These use particulates rather than fibers and are formulated to match the coefficient of thermal expansion of electronic substrates in order to alleviate thermally induced stresses. The development of both types of these materials as viable weight-saving substitutes for the traditional methods of thermal control for electronics packaging and also for spacecraft thermal control applications are the subjects of this report.

Introduction

The thermal design of spacecraft and spacecraft electronics packages has traditionally used either high thermal conductivity metals or heat pipes to conduct waste heat to remote space-facing radiators. Recently, high thermal conductivity continuous graphite fiber-reinforced metal matrix composites (MMC's) have become available that can save much weight over these traditional materials. These composites have a much higher thermal conductivity than the pure metals. The objective of this work was to develop these materials as viable weight-saving substitutes for the traditional methods of conductive heat transfer for electronic component temperature control.

Continuous fiber-reinforced metal matrix composites have been in the research stage for many years. For most of this period, however, these MMC's were only available in moderate fiber-to-matrix volume ratio and with lower modulus and hence lower thermal conductivity graphite fibers. The advent of high modulus graphite fibers brought with it the property of enhanced thermal conductivity of the basic fibers. Another development was finding methods to fabricate these composites with a considerably higher fiber-to-volume ratio. The combined effect of enhanced fiber thermal conductivity along with a higher density of fibers in the MMC has led to the recent use of these materials as solid heat pipes.

These composite materials are now available for solving problems regarding spacecraft and electronic packaging thermal conduction. The use of these materials can bring about weight savings of from 50 to 70% over structural aluminum. Even larger weight savings will be possible in the future. Another advantage is that these materials can be used anywhere in a spacecraft or an electronic package without the gravitational testing and plumbing complexities that accompany the use of liquid heat pipes. A spinoff of this effort was the development of MMC's using particulates rather than fibers that had the added property of matching the coefficient of thermal expansion of silicon chips. These MMC's can be used as replacements for the heavier conventional materials used for electron device heat sinks.

The basic materials properties, including MMC types and comparisons with other materials, and their applications to electronics and spacecraft, are the subjects of this report.

Basic Materials Properties

Metal Matrix Composite Types

There are two varieties of metal matrix composites (MMC's). One has continuous reinforcements and anisotropic properties, and the other has discontinuous reinforcements and approximately isotropic properties.

The continuous reinforcements are fibers and are usually as long as the geometry of the part will allow. Typical materials found as continuous fiber reinforcements in composites are graphite, steel, tungsten, and various ceramics such as boron and silicon carbide. Fibers can either occur singly, as found in 0.13 mm (0.0056 in.) diameter boron fibers, or as part of a bundle or tow, as found in graphite yarns composed of thousands of fibers, each approximately 5 to 10 μ m (a few millionths of an inch) in diameter (see Fig. 1).

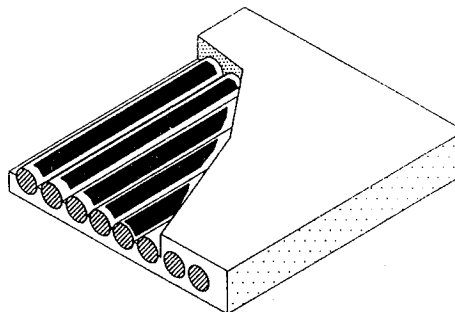


FIGURE 1. - CONTINUOUS REINFORCEMENT COMPOSITE.

Discontinuous reinforcements are powders or short fibers. These have individual reinforcing elements that are much smaller than the part being fabricated. Powders can consist of chopped fibers, whiskers, platelets, and particulates, depending on their relative size and shape. Typical materials used as discontinuous reinforcements are ceramics (e.g., silicon carbide and boron carbide) and short fibers of chopped graphite and chopped steel wire (see Fig. 2).

Almost any common metal can serve as the matrix for an MMC. Aluminum, magnesium, copper, steel, titanium, and others are used as matrices. The metal is usually dictated by the design requirements of the application, such as operating temperature, weight limitations, stiffness, or thermal conductivity.

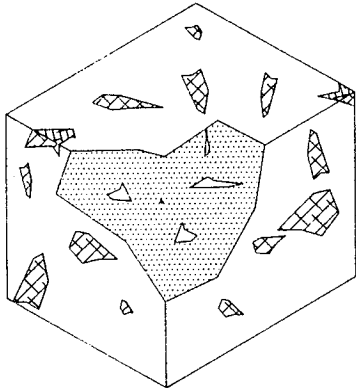


FIGURE 2. - DISCONTINUOUS REINFORCEMENT COMPOSITE.

Details of the manufacturing techniques of metal matrix composites are closely guarded secrets of the various manufacturers. Fabrication of a fiber-reinforced composite article generally starts by collimating the fibers into a preform. The metal is applied to the fiber preform and the material consolidated at high temperature and pressure. The manufacturing process often integrates unreinforced matrix foils at the exterior surfaces, leaving no exposed reinforcement (see Fig. 3).

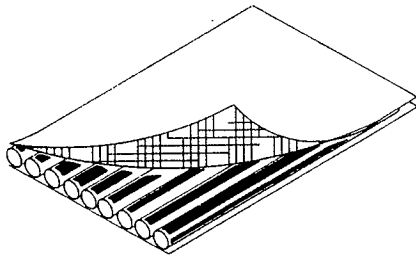


FIGURE 3. - FIBER-REINFORCED COMPOSITE FABRICATION.

The most commonly manufactured forms of fiber-reinforced composites are sheets and tubes. The number of post-consolidation manufacturing processes that can be applied to continuous fiber-reinforced composite materials is limited. The material can be cut to size and shape using conventional techniques such as drilling, shearing, sawing, and electrical discharge machining. It can be joined with adhesives, welds, solders, and mechanical fasteners. It can be formed into limited non-planar surfaces with appropriate tooling and other processes. It cannot be extruded or forged (see Fig. 4).

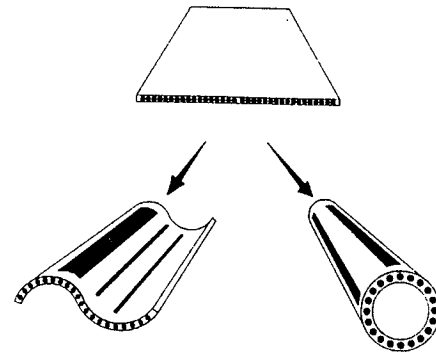


FIGURE 4. - MANUFACTURED SHAPES OF FIBER-REINFORCED COMPOSITE.

Manufacture of discontinuous-reinforcement composites is primarily grouped into powder metal processes and casting processes. In the former, powders of the matrix metal and the reinforcing agent are blended together and the mixture consolidated into the finished material at high temperature and pressure (see Fig. 5).

The most commonly fabricated form of particulate-reinforced metals is a cylindrical billet. Many relatively conventional manufacturing processes can be applied after consolidation, including extrusion, forging, milling, turning, drilling, spinning, and rolling. The material can be joined by welding, adhesive bonding, soldering, mechanical fastening, and friction welding.

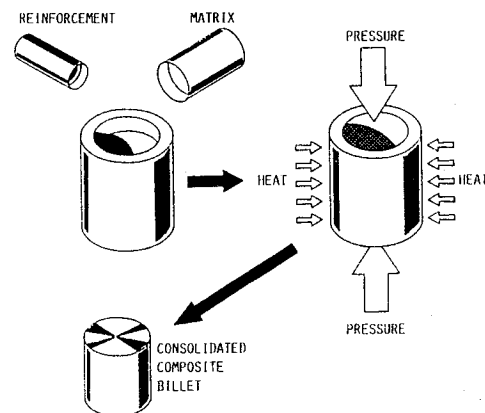


FIGURE 5. - MANUFACTURING SEQUENCE FOR DISCONTINUOUS REINFORCEMENT COMPOSITE.

Casting techniques generally start with the preparation of a porous preform of reinforcement material approximating the shape to be fabricated. The preform is positioned in a mold shaped like the finished part and molten metal is then infiltrated into the preform, filling out the part (see Fig. 6). Casting techniques can result in nearly finished parts. Post-casting manufacturing is generally limited to final cleanup of the part and to finish machining where needed. Billet and "pig" forms of composite are also cast.

Material Properties

The material properties of the discontinuous- and continuous-reinforcement composites can be characterized as isotropic and anisotropic, respectively. Reinforcing powders typically found in discontinuous reinforcement MMC's are randomly oriented, resulting in material properties that are not dependent upon

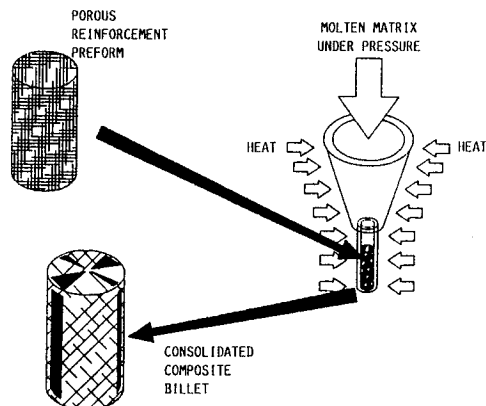


FIGURE 6. - SQUEEZE-CAST COMPOSITE MANUFACTURE.

direction. The fibers in a continuous-reinforcement MMC are typically oriented parallel to one another in discrete layers. In a given layer, the material properties are governed by the fiber properties in the direction of the fiber axis and by the matrix properties in the transverse direction. Since the fibers and matrix usually have radically different properties, each property of the composite depends upon the direction in which the measurements are taken (see Fig. 7).

Depending upon the type and amount of reinforcement and the type of matrix, a discontinuous composite is typically stiffer, stronger, less ductile, and has a lower coefficient of thermal expansion than the unreinforced metal. Thermal conductivity and density are dependent upon the selection of the matrix and reinforcement, and can be either increased or decreased.

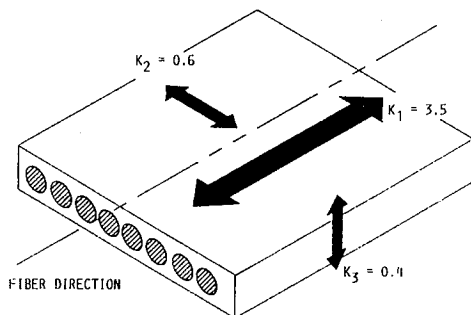


FIGURE 7. - ANISOTROPIC PROPERTIES IN FIBER-REINFORCED COMPOSITE. PROPERTY ILLUSTRATED IS THERMAL CONDUCTIVITY MEASURED IN W/CM K.

A continuous MMC typically has high strength and stiffness with low ductility and thermal expansion in the fiber direction. Transverse to the fibers, the strength and stiffness are lower (matrix dependent) and the thermal expansion is similar to the matrix. The change in density depends upon the relative densities of the constituents.

The anisotropy in the material properties of a continuous fiber-reinforced composite can be reduced by arranging the layers of fibers in different directions. Cross-plying fiber layers balances the longitudinal and transverse properties, resulting in planar-isotropic properties (see Fig. 8).

Some graphite fibers have two particularly useful properties: high thermal conductivity and negative coefficient of thermal expansion. The thermal

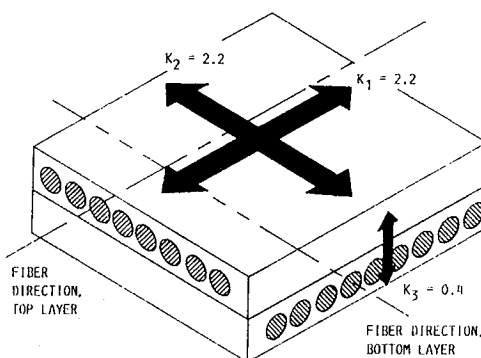


FIGURE 8. - PLANAR-ISOTROPY IN CROSS-PLY COMPOSITE. PROPERTY ILLUSTRATED IS THERMAL CONDUCTIVITY MEASURED IN W/CM K.

conductivity of some graphite fibers with a particular crystal structure has been measured as high as 2000 W/m K. For comparison, copper has a thermal conductivity in the high three hundreds and silver in the low four hundreds. The combination of these high thermal conductivity fibers with a metal matrix can produce composites with excellent conductive heat transfer properties. Thermal conductivities can be well in excess of the best metals, and densities are normally lowered.

The crystal structure of graphite also results in a negative coefficient of thermal expansion (CTE) in the fiber direction. When the material is heated, it gets smaller. This is in contrast to nearly all other materials, including the metals used in MMC's. Combining the negative CTE of the graphite with the positive CTE of a metal results in a material that balances the two effects. By adjusting the ratio of metal to graphite and adjusting the orientation of the fibers, a composite can be created that does not change its linear dimension when the temperature changes; that is, there is a zero coefficient of thermal expansion. The two properties (high thermal conductivity and near zero CTE) of the graphite fiber-reinforced composite described can be maximized only in continuous fiber composites. They do not transfer as significantly to discontinuous composites or to composites with chopped fibers.

Of the materials commonly encountered in electronic systems (metals, ceramics, and organics), metal matrix composites are most similar to metals. Metals, in general, (1) are stiffer than organics and less stiff than ceramics, (2) have greater thermal conductivity than either organics or ceramics, (3) have more ductility than ceramics and less than some organics, and (4) have a higher coefficient of thermal expansion than ceramics and less than organics.

The addition of reinforcing agents to the metallic composite can move the properties of the composite in the desired direction. Properties of other materials can be matched. MMC's can be as stiff as ceramics but without the extreme low ductility of ceramics. They can have a CTE as low as ceramic and they can have greater thermal conductivity than any other material.

Applications

General

Solutions to conductive heat transfer problems involving either electronics packages or spacecraft systems are made possible at great weight savings by the use of MMC's. Figure 9 is a plot that compares the thermal conductivity of copper to a graphite/aluminum composite over a large temperature range. The composite exceeds the thermal conductivity of pure copper over the temperature range from -50 to 100 °C (the operating range of most electronic components). Figure 10 is a plot of the specific thermal conductivity versus CTE that compares both continuously (fiber) reinforced MMC materials and discontinuously (powder) reinforced MMC composite materials to materials generally used for electronics packaging and spacecraft construction purposes. The composite materials in the figure form two distinct groups. These are anisotropic low distortion, high longitudinal heat conductivity materials (continuous fiber), and matched coefficient of thermal expansion materials (discontinuous powder). Figure 11 is a bar graph of the various material types versus specific thermal conductivity. These charts illustrate the great weight advantage that the MMC's have over materials conventionally used for thermal control in electronics packaging or spacecraft construction applications.

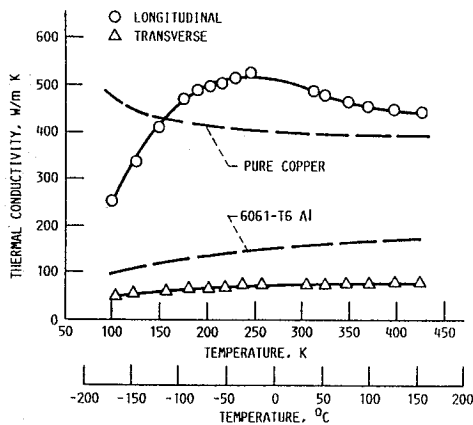


FIGURE 9. - THERMAL CONDUCTIVITY OF 48.5 v/o P-X-7/6061 Al (D-1607).

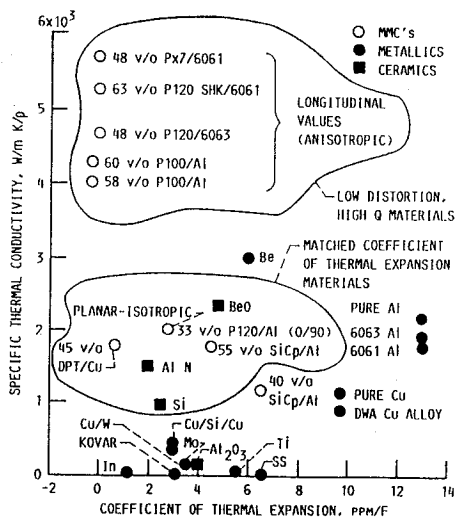


FIGURE 10. - SPECIFIC THERMAL CONDUCTIVITY AND CTE OF MMC MATERIALS AND CONVENTIONAL ELECTRONIC MATERIALS.

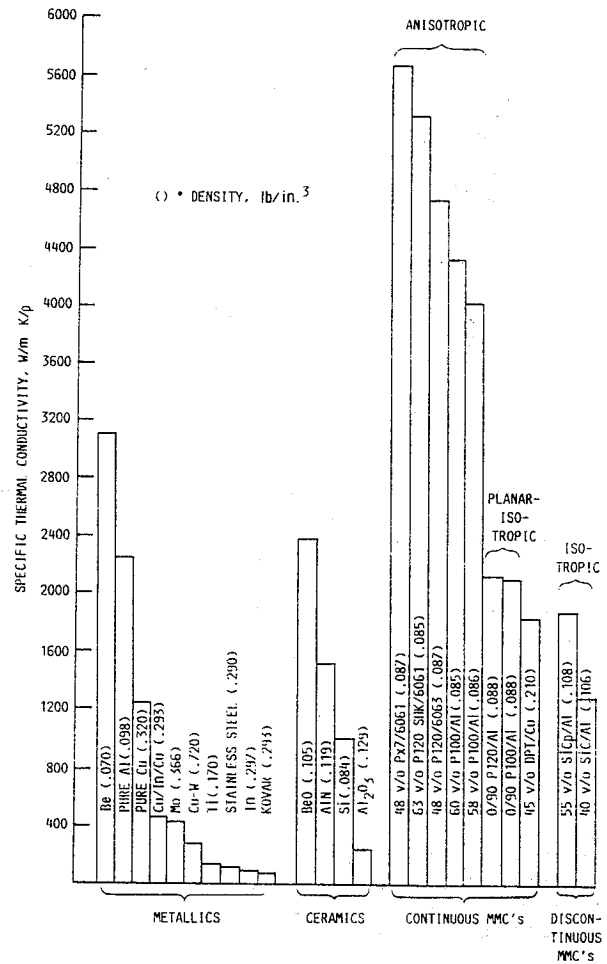


FIGURE 11. - SPECIFIC THERMAL CONDUCTIVITY OF MMC MATERIALS AND CONVENTIONAL ELECTRONIC MATERIALS.

Electronics Applications

For electronics chip carriers, discontinuously reinforced MMC's using ceramic powder particulates can be used to create a substrate, the CTE of which closely approximates the silicon substrate of the electronic chip (see Fig. 10). This can result in weight savings of up to 30:1 compared with the use of Kovar (see Fig. 11) when aluminum is used as a matrix and when the design criterion is a fixed heat flux.

For electronic systems, continuous fiber-reinforced composites can be used to conduct heat at weight savings of 2:1 or better when unidirectional high-modulus graphite is used in an aluminum matrix. This advantage can be realized by using present-day, readily available materials. If the highest thermal conductivity graphite could be used, this ratio could theoretically become 8:1. If increased thermal conductivity is desired orthogonal to the fiber direction, it is only necessary to cross successive plies slightly in order to achieve good cross-ply conductivity while still maintaining the predominant thermal conductivity in the lineal direction. This happens because the cross-ply thermal conductivity is proportional to the sine of the cross-ply half-angle, while the lineal thermal conductivity is proportional to the cosine of that small half-angle. At a half-angle of 45°, the thermal conductivity becomes approximately planar isotropic.

An application for a high lineal thermal conductive MMC would be conducting heat away from any source in a small tightly-packed area that precludes the use of liquid heat pipes. This would include small high-powered chip carriers and high-power transistors in power processor applications and many others. Figure 12 illustrates a phased array antenna concept. Here, graphite/aluminum MMC solid heat pipes are used to conduct the waste heat from the RF circuit boards to remote deep space-facing radiators.

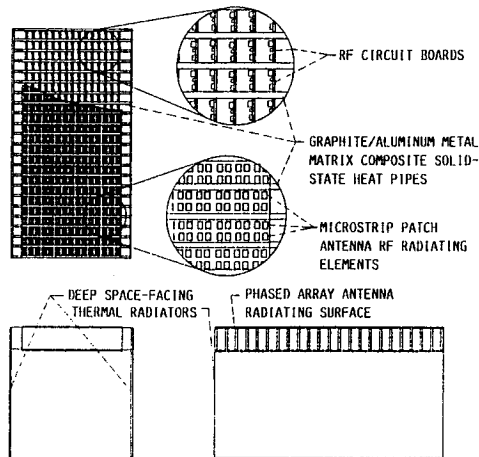


FIGURE 12. - PHASED ARRAY ANTENNA CONCEPT.

Planarly isotropic high thermal conductivity MMC sheets could be used as a substrate for circuit boards to either greatly reduce weight at a fixed heat flux or greatly increase reliability at the same weight by reducing component temperatures. They could also be used to remove the heat from very large scale integrated circuits (VLSIC's) where they could be formulated to match the coefficient of expansion of the circuit substrates. In general, they could be used anywhere that the combined properties of high thermal conductivity, matching coefficient of thermal expansion, and reduced weight are desired.

General Thermal Control Applications

MMC's could be used as spacecraft radiators to conduct heat away from liquid heat pipes. Slightly cross-plyed high thermal conductivity sheets could be used for this purpose. Heavier plates of the material could be used anywhere that high heat fluxes must be conducted to remote space-facing radiators and that the use of liquid heat pipe is restricted because of ground test limitations in a 1 g. field (because panels containing heat pipes are normally restricted to horizontal operation on Earth).

Large continuously-fiber-reinforced cross-plyed sheets could be used as face sheets for the honeycomb sandwich panels used in spacecraft construction. These panels generally have embedded heat pipes and depend upon the face sheets to both conduct heat from the electrical components to the heat pipes and to distribute the heat for radiation to space. Where large heat fluxes must be conducted, doublers of these materials could be adhesively bonded to the honeycomb face sheets (see Fig. 13).

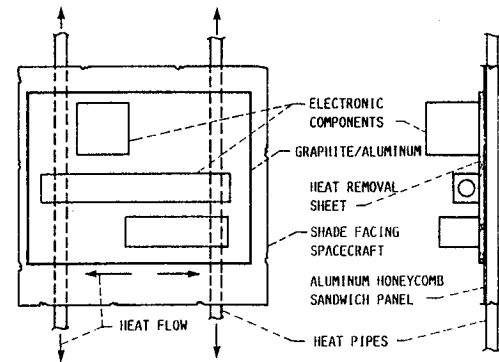


FIGURE 13. - TYPICAL SPACECRAFT HEAT REMOVAL SHEET APPLICATION.

Other Applications

Other applications for continuously-reinforced high thermal conductivity MMC sheets would be as leading edges for hypersonic aircraft wings. Here, the thermal conductivity could be optimized to conduct the heat away from the leading edge to a lower temperature area where the heat could be exchanged convectively.

The many applications for discontinuously- or powder-reinforced MMC's are too numerous to list. Sample uses to date include aircraft electronic racks, guidance components, and inside structures, as well as pistons, cylinder liners, connecting rods, wrist pins, and fuel injection parts for internal combustion engines. Other automotive uses include brake rotors, brake calipers, wheels, and driveshafts. In general, these materials can be used wherever there is a need for combinations of the qualities of increased stiffness and strength, low or matching CTE, wear resistance, and low mass or moment of inertia. These materials are also much lower in cost than the continuous-fiber-reinforced MMC.

Cost

As in the case of any new or emerging technology, the cost of these materials in precursor or finished form is high but subject to rapid change. The cost of bars or sheets of continuous fiber-reinforced graphite (100 Mpsi modulus) aluminum MMC is generally \$2,000 to \$4,000 per pound. The cost of each item using these materials can vary according to the fibers chosen and the final configuration. The cost of discontinuously powder or particulate reinforced MMC in small quantities is generally a few hundred dollars per pound in simple extruded or rolled form, depending again on composition and final configuration. The current cost of launching a spacecraft to low Earth orbit is \$5,000 to \$10,000 per kilogram (\$2,000 to \$4,000 per pound). The cost of launching a spacecraft to geosynchronous orbit can be ten times as high. Thus, the use of these higher cost materials in space as a weight-saving measure can be easily justified.

Summary and Conclusions

Much effort has gone into the development of MMC's for use in space in recent years. Continuously-fiber-reinforced MMC's (graphite/

aluminum) can now be used to reduce the weight of cores in PC boards by one-third to one-half. The packaging density of high-power electronic components can now be doubled by using these materials, and the weight of a deep space-facing thermal radiator can now be cut in half. Graphite fibers are now being developed that could increase the benefits of using these materials by a factor of four if used in an aluminum matrix.

Discontinuously or powder or particulate reinforced MMC's can be used to match heat sink and electronic chip substrate coefficients of thermal expansion for eliminating the formation of circuit opens or damage to the ceramic devices when the circuits are thermally cycled. These materials can also be used to either reduce the weight of these heat sinks by up to one-third or to increase reliability by lowering the component operating temperature.

While the cost per unit weight of these materials is currently high, their use in spacecraft

electronics packaging or spacecraft thermal control systems can now be easily justified on a weight or reliability basis.

Acknowledgment

This work was sponsored by the NASA Lewis Research Center as Phase I and Phase II Small Business Innovation Research (SBIR) contracts. The unique composite materials reported herein were developed by DWA Composite Specialties, Inc. The principal investigators were E.C. Supan, E.J. Levin, and T.A. Loftin. M. van den Bergh performed the marketing and applications study that has developed much commercial interest in the results of this program. President J.F. Dolowy, Jr. and Vice President B.A. Webb contributed much to the fabrication, technical, and marketing aspects of this effort.

Report Documentation Page

1. Report No. NASA TM-102434 AIAA-90-0783		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Applications of High Thermal Conductivity Composites to Electronics and Spacecraft Thermal Design				5. Report Date	
				6. Performing Organization Code	
7. Author(s) G. Richard Sharp and Timothy A. Loftin				8. Performing Organization Report No. E-5175	
				10. Work Unit No. 324-02-00	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the 13th International Communication Satellite Systems Conference sponsored by the American Institute of Aeronautics and Astronautics, Los Angeles, California, March 11-15, 1990. G. Richard Sharp, NASA Lewis Research Center; Timothy A. Loftin, DWA Composite Specialties, Inc., 21119 Superior Street, Chatsworth, California 91311-4393 (work performed under NASA Contract NAS3-24896).					
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17. Key Words (Suggested by Author(s)) Composite Electronics Thermal conductivity			18. Distribution Statement Unclassified--Unlimited Subject Category 18		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 6	
				22. Price* A02	

